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As part of our work on APOSR Grant F-49620-00-1-0319, "Shock Wave And Boundary Layer Control For Aero-Optic Applications," we have explored slot-injection of helium into Mach 8 boundary layers, over a range of Reynolds numbers. We injected helium into a fully turbulent boundary layer as well as transitional boundary layers. Downstream of the slot, we see a large-scale organization of the boundary layer (the appearance of longitudinal vortex-like structures that are very stable in spanwise location). We see this with very low helium mass flow rates (a few percent of the freestream value). Current work is directed toward understanding this phenomenon and detailed studies of the injection region using tlow visualization and PIV are in progress to determine the formation of the streamwise vortices.

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SHOCK WAVE AND BOUNDARY LAYER CONTROL FOR AERO-OPTIC APPLICATIONS

Covering the Period 11/1/99 through 1/31/02

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FINAL TECHNICAL REPORT

SHOCK WAVE AND BOUNDARY LAYER CONTROL FOR AERO-OPTIC APPLICATIONS

AFOSR GRANT F-49620-00-1-~~0319~~ 0139

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Abstract

As part of our work on AFOSR Grant F-49620-00-1-0319, "Shock Wave And Boundary Layer Control For Aero-Optic Applications," we have explored slot-injection of helium into Mach 8 boundary layers, over a range of Reynolds numbers. We injected helium into a fully turbulent boundary layer as well as transitional boundary layers. Downstream of the slot, we see a large-scale organization of the boundary layer (the appearance of longitudinal vortex-like structures that are very stable in spanwise location). We see this with very low helium mass flow rates (a few percent of the freestream value). Current work is directed toward understanding this phenomenon, and detailed studies of the injection region using flow visualization and PIV are in progress to determine the formation of the streamwise vortices.

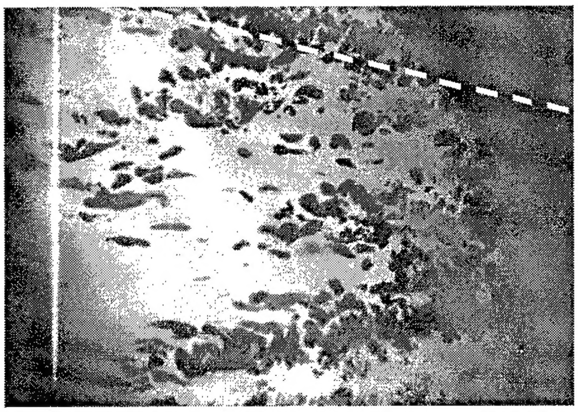
Report

The strong influence of low levels of helium injection into a Mach 8 transitional boundary layer was demonstrated first by Erbland *et al.* 1997 and Etz 1998, The experiments appeared to show that helium injection through a spanwise slot delays transition indefinitely. Interestingly, injection of air at the same location with the same momentum flow rate had no significant effect. While the phenomenon was far from understood, it was speculated that injection of helium effectively reduces the Reynolds number near the wall (the kinematic viscosity of helium is a factor of 8 higher than that of air at the same temperature), inhibiting turbulent mixing. In support of this conjecture, sodium fluorescence images clearly showed the presence of a relatively thin, highly stable helium layer near the wall.

More detailed studies by Auvity *et al.* (2000, 2001) using Filtered Rayleigh Scattering (FRS) and a new MHz imaging system revealed the three-dimensional character of the flow field affected by the helium. These results permitted a more complete understanding of the effects of helium injection on hypersonic boundary layers, and its possible use in aero-optics. In particular, the effect of helium injection into a fully-developed turbulent boundary layer at Mach 8 was studied, and some mechanisms for the effects of helium injection were offered.

Briefly, the FRS visualizations showed that helium injection at all Reynolds numbers introduced a highly organized but fully three-dimensional character to the flow downstream of the slot. According to Erbland (2000), the strong contrast in greyscales in FRS images mark the boundary between the relatively hot boundary layer fluid (dark) and the external freestream fluid (bright). FRS images, therefore, provide information on the boundary layer edge. In figure 1, planform views are shown with the laser sheet located 4.5 mm away from the surface, where the undisturbed

boundary layer thickness is about 8 mm. Here, J is the ratio of the jet momentum to the freestream fluid momentum, and X is the distance of the slot from the leading edge of the plate. Conditions 1. 2 and 3 correspond to unit Reynolds numbers of 14 x 10^6, 16 x 10^6, and 16 x 10^6, respectively, together with corresponding X values of 70, 300, and 220 mm, and slot widths of 1, 1, and 3mm. For Condition 1, the injection was into a transitional boundary layer, and for Conditions 2 and 3 the injection was into a turbulent boundary layer (Re_θ approximately 4000). In figure 1, the streamwise field of view is from about 290 to 460 mm. A dark area of relatively constant width marking the helium injection is clearly seen, surrounded by undisturbed boundary layer fluid. The width of this region is slightly larger than the width of the injection slot, and it is about the same for all conditions studied.



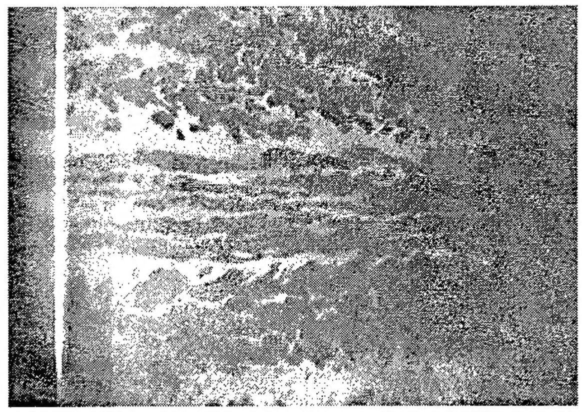


Figure 1: Planform views of the boundary layer at y = 4.5 mm for Condition 1: (left) without helium injection; (right) with helium injection, J = 0.13. The flow is from left to right.

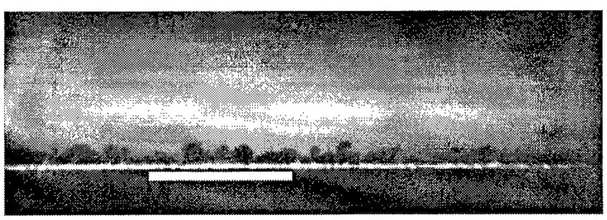


Figure 2: Spanwise view of the boundary layer 300 mm downstream of the leading edge for Condition 1:(left) without helium injection; (right) with helium injection, J = 0.13. The flow is out of the page.

Spanwise views are shown in figure 2 for the same stagnation conditions as in figure 1. The lateral location of the injection slot is shown by the white horizontal line. The troughs represent a decrease in the boundary layer thickness and appear as bright lines in figure 1 suggesting that the boundary layer structure seen on images in figure 2 is maintained in the streamwise direction. Time-averages of about thirty images confirm that the troughs have a stable position on average.

The successive spanwise crests and troughs can be interpreted as a series of entrained fluid motions toward to the wall alternating with ejected fluid motions outward from the wall. Since the spanwise organization of the boundary layer seems to persist in the streamwise direction, this structure may be attributed to the existence of streamwise counter-rotating vortices in the boundary layer. Many images strongly suggested that counter-rotating motions are active in the boundary layer. If streamwise vortices occur in the boundary layer downstream of slot injection of helium, the appearance of a crest in the averaged spanwise images may correspond to the presence of one pair of counter-rotating vortices. Such streamwise vortices, also called Gortler vortices, have been

observed in boundary layers submitted to concave surface curvature. Consequently, the appearance of the streamwise vortices may be associated with concave streamline curvature in the region where the helium is injected.

Three-dimensional images of the boundary layer edge were acquired using a "pulse-burst" laser system in conjunction with a high-speed CCD camera. Complete details of the laser system are given in Wu et al. (1998). Briefly, the Nd:YAG laser has the capability of producing a "train" of 30--40 high energy pulses with pulse separation times as shorts as one microsecond. The laser is paired with a novel CCD framing camera developed by Princeton Scientific Instruments, Inc. that can frame at rates up to 1 MHz. This imaging system can collect a time sequence of 20--30 images. The chosen repetition rate is 500 kHz in order to obtain high laser pulse energy and maximize the sampling window. If the laser sheet is oriented normal to the wall in the spanwise direction, the sequential images can be assembled into a quasi-three-dimensional volumetric image, as long as Taylor hypothesis can be invoked. This requires that the large-scale motions evolve over distances large compared to the boundary layer thickness.

A 30-frame sequence obtained without injection is presented as a volumetric image in figure 3a. The individual images have been stacked in temporal order with the first frame on the right and the last frame on the left. The spacing in the streamwise direction was set using an average convection velocity. In figure 5a, the convection velocity was chosen to equal the freestream velocity (1140 m/s). The convection velocity of the large scale motions is probably slightly lower than that value Huntley (2000). The gap between the frames were filled in by linear interpolation of the greyscales. The surface illuminated in figure 3a is actually the interface between the condensed and sublimated carbon dioxide (nominally the instantaneous boundary layer edge). The interface is made visible by making all the freestream greyscales (the bright region) transparent. The direction of light illumination can be adjusted to create the shadow effect and accentuate the three dimensional nature of the boundary layer.

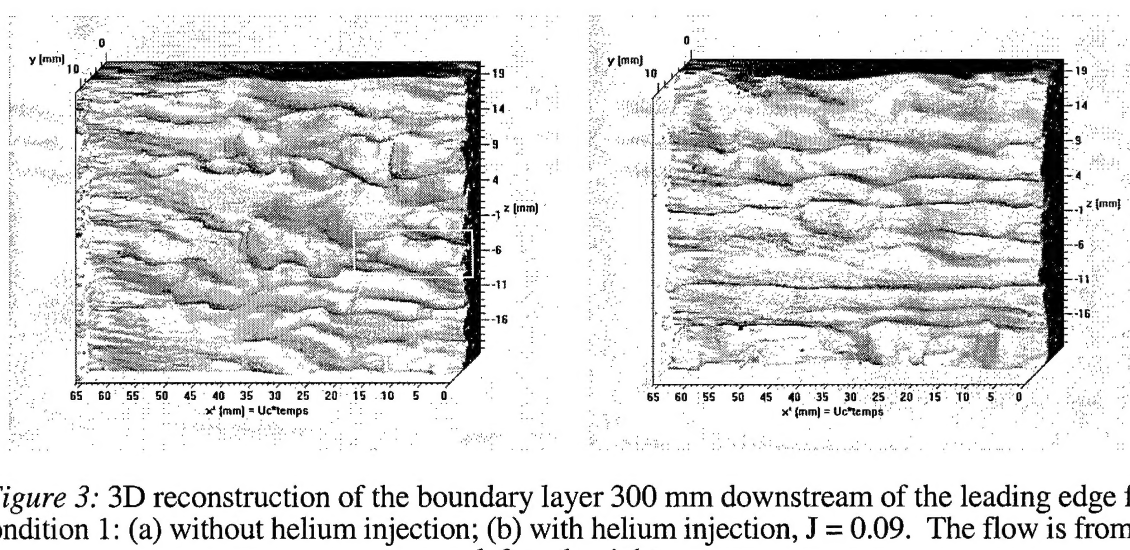


Figure 3: 3D reconstruction of the boundary layer 300 mm downstream of the leading edge for Condition 1: (a) without helium injection; (b) with helium injection, J = 0.09. The flow is from the left to the right.

Figure 3b represents a reconstruction of the boundary layer under Condition 2 with helium injection for J = 0.09. The physical size of the 3D representation is similar to that shown in figure 3a. The spanwise structure of the boundary layer shown in the time-averaged spanwise images can also be clearly in figure 3b. Crests and troughs with a significant streamwise extent are present, in positions similar to that found in the time-averaged images. More smaller-scale disturbances can be observed in the crests for J = 0.13 than for J = 0.09, but the troughs are deeper for J = 0.13.

It was recently demonstrated by Auvity et al. (2001) that helium injection at higher Reynolds numbers, that is, into a fully turbulent boundary layer (Conditions 2 and 3) produces a very similar organization of the boundary layer (what appear to be longitudinal vortex-like structures that are very stable in spanwise location). We see this with a helium mass flow rate that is about three times as large (we increased the slot width so that the mass and momentum fluxes are still the same as before, but the flow rate tripled, Condition 3).

Two hypotheses are advanced: for the flow patterns produced by helium injection: (1) that the vortices are produced by streamline curvature through a Taylor-Gortler instability, or (2) that they are produced as necklace vortices by the three-dimensionality of the slot injection as the jet breaks up into spanwise segments. To explore these conjectures further, surface oil flow visualization using silicon oil doped with TiO_2 was used. An example is shown in figure 4. Converging and diverging surface streamlines are evident downstream of the slot, which tends to support the presence of streamwise vortices. In addition, the large-scale three-dimensionality of the surface flow induced by injection is evident, suggesting that the effects of injection have a streamwise length scale of order 10 slot widths.

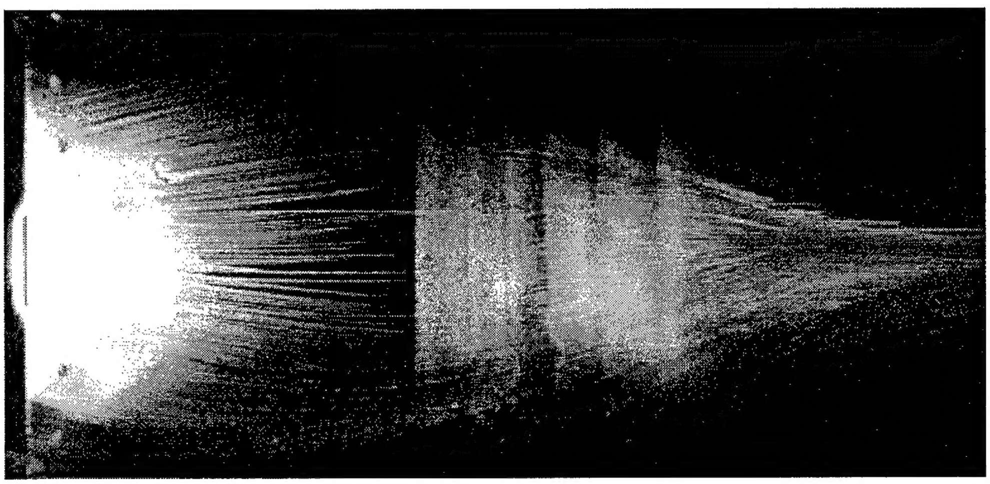


Figure 4: Surface flow visualization with helium injection, conditions similar to Condition 1, with $J = 0.09$. The flow is from the left to the right. The slot is visible at the far left.

To obtain more insight into vortex motions inside the boundary layer with and without helium, PIV was attempted. Three major issues are: (1) the method of seeding the particles into the flow; (2) selecting the right size particles; (3) sufficient camera resolution. In the results reported here, TiO_2 particles were used (typical diameter 0.2 micron) and they were introduced into the injected helium by passing the helium through a seeder of cyclonic design. Clogging did not appear to be a problem, and the seeding density was intermittent, but occasionally a reasonable seeding was captured for further analysis. An example is given in figure 5. The laser sheet was located 3.2 mm above the plate, and the time interval between pulses was 1 μs.

The corresponding velocity vector and velocity contour fields are shown in figure 6. It appears that the resolution of the camera and the particle image brightness are sufficient for PIV analysis. No attempt has been made at an error analysis, but work is in progress. The issue of particle lag is especially important. What is encouraging is that the velocity magnitudes seem reasonable (the freestream velocity is 1140 m/s, and the boundary layer thickness is about 6 mm at this location). The flowfield also appears to be largely symmetric in the region shown in this figure, and the incursion of high-speed fluid on the edge of the jet is evident.

Current work includes the study of helium injection in a transonic boundary layer, and finding ways to enhance the effects of helium injection as a means for flow control. In particular, we are interested in determining if the organizing effects due to helium injection in hypersonic flow will works in transonic flow. We also intend to study the use of vortex generators upstream of the concave area to produce a controlled disturbance that is amplified by destabilizing curvature to lock the vortices into pre-determined spanwise locations. This will be useful design information if the helium injection is to be used in the control of aero-optic applications. Such devices may also enhance the stabilizing influence of the vortices. In addition, we will increase the viscosity of helium by heat or try another 'viscous' gas. If the kinematic viscosity of the injected gas is a key parameter, can we find a 'better' gas than helium, or does heated helium change something?

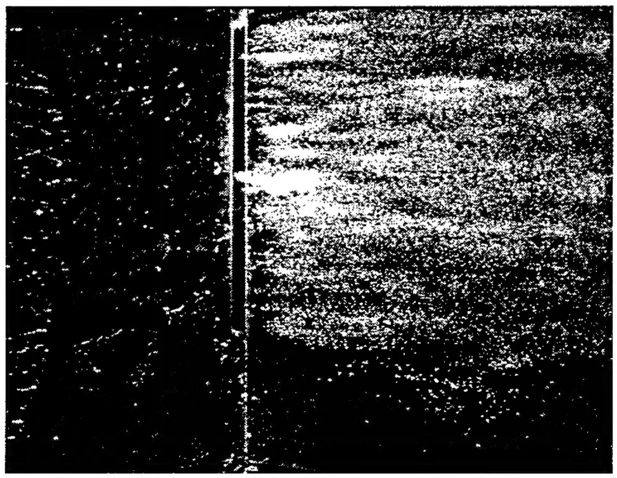


Figure 5: Double-pulsed image of titanium dioxide particles carried by helium injection, J = 0.09. The flow is from the left to the right. The slot is visible left of center.

Finally, in order to quantify the aero-optic benefits of helium injection, we propose to construct a unique MHz rate Shack-Hartmann sensor. The aero-optic diagnostic approach was developed with help from John Lowrance of Princeton Scientific Instruments, who designed and constructed the PSI-1 MHz rate framing camera used in the three-dimensional imaging system described earlier, and Mike Holden of CALSPAN. In the two-dimensional version we propose to introduce a point source of laser light through a laminar flow plate, pass it through the test flow, through a sapphire window in the test plate, and direct it through a plano-convex lens to a lenticular array placed in front of the PSI-1 camera, enabling MHz rate imaging of the wavefront distortion, constituting, in effect, a MHz rate Shack-Hartmann wavefront sensor. Each lenslet in the array produces a spot on the CCD array, and the average wavefront slope over the lenslet aperture will determine the location of this spot. The resulting array of wavefront slopes can then be used to reconstruct the wavefront, to the spatial accuracy determined by the lenticular array. The field of view is expected to be about 1.5 in. by 1.5 in., which matches well with the 1 in. width of the helium injection slot, and is equivalent to about 5 local boundary layer thicknesses.

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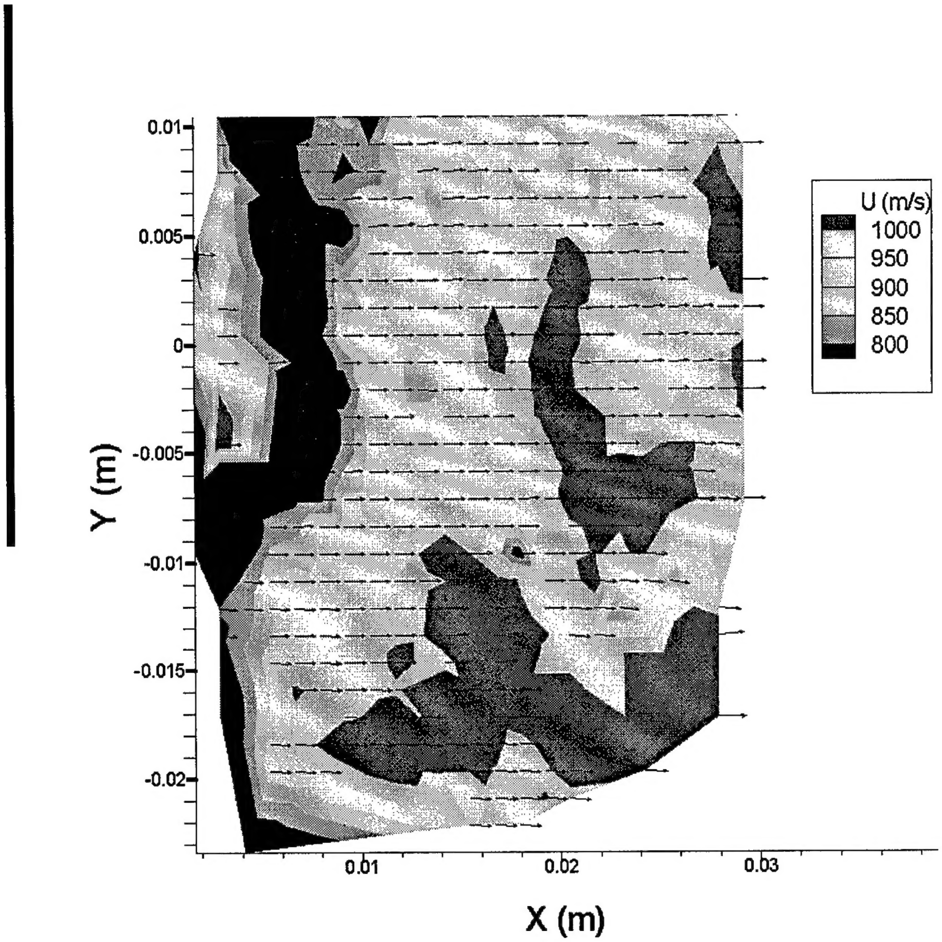

Figure 6: Velocity contours corresponding to figure 5. The flow is from the left to the right. The lateral position of the slot is indicated by the black vertical line.

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Auvity, B., Etz, M., Huntley, M., Pingfan Wu and Smits, A.J. "Control of Hypersonic Boundary Layers by Helium Injection," AIAA Paper 2000-2322, Fluids 2000 Conference, Denver, Colorado, June 19-22, 2000.

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